102439/ RR[redacted]A

2

(12) UK Patent Application (19) GB (11) 2 245 115 (13) A

(43) Date of A publication 18.12.1991

(21) Application No 9109898.8

(22) Date of filing 28.04.1987

Date lodged 08.05.1991

(62) Derived from Application No 8709998.2 under Section 15(4) of the Patents Act 1977

(71) Applicant
Racal Communications Equipment Limited

(Incorporated in the United Kingdom)

Western Road, Bracknell, Berkshire, RG12 1RG, United Kingdom

(72) Inventor
Christopher John Andrews

(74) Agent and/or Address for Service
Mathisen Macara & Co
The Coach House, 6-8 Swakeleys Road, Ickenham, Uxbridge, Middlesex, UB10 8BZ, United Kingdom

(51) INT CL[5]
G01R 23/20, H03F 1/32

(52) UK CL (Edition K)
H3W WUL
G1U UR2320
H3T T2E T2T2X T3V

(56) Documents cited
GB 1529471 A

(58) Field of search
UK CL (Edition K) **G1U UR2320, H3W WUL**
INT CL[5] **G01R, H03F**
On-line databases:WPI

(54) Measuring distortion

(57) In a method of analysing the distortion produced by a linear power amplifier two tones are applied to the amplifier 20 and the resulting down-mixed signal at 26 is periodically sampled at 28 and subjected to a FFT in order to derive the spectrum and plot the amplitude and phase distortion against the two tone amplitude. Analysis of the results of such testing throughout the frequency range of the amplifier allows pre-distortion circuits to be designed to compensate for distortion produced by the amplifier over the complete operating frequency range of a transmitter. The predistortion circuits may include combinations of diodes with resistors, capacitors or inductances.

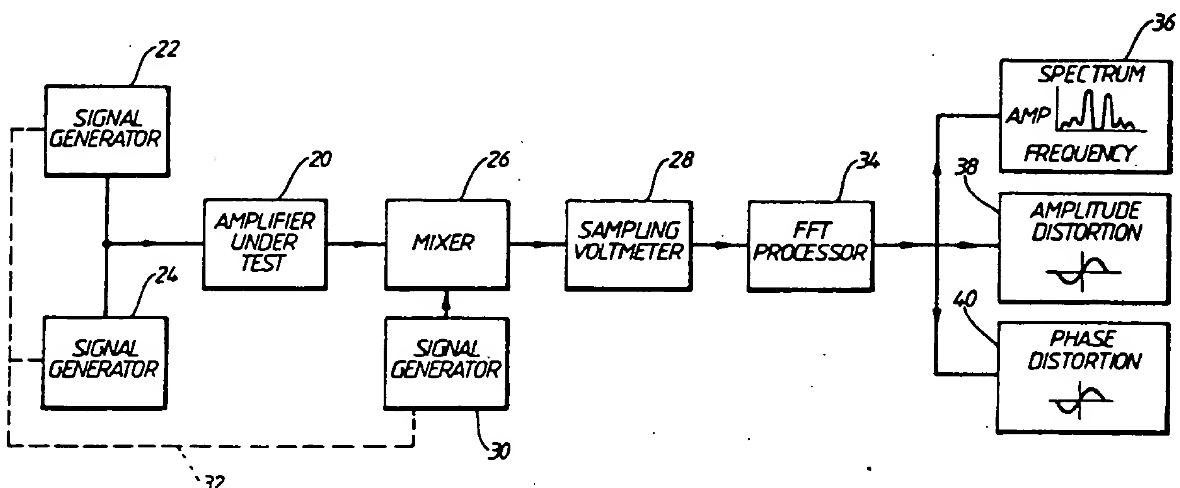


FIG. 4.

The date of filing shown above is that provisionally accorded to the application in accordance with the provisions of Section 15(4) of the Patents Act 1977 and is subject to ratification or amendment.

GB 2 245 115 A

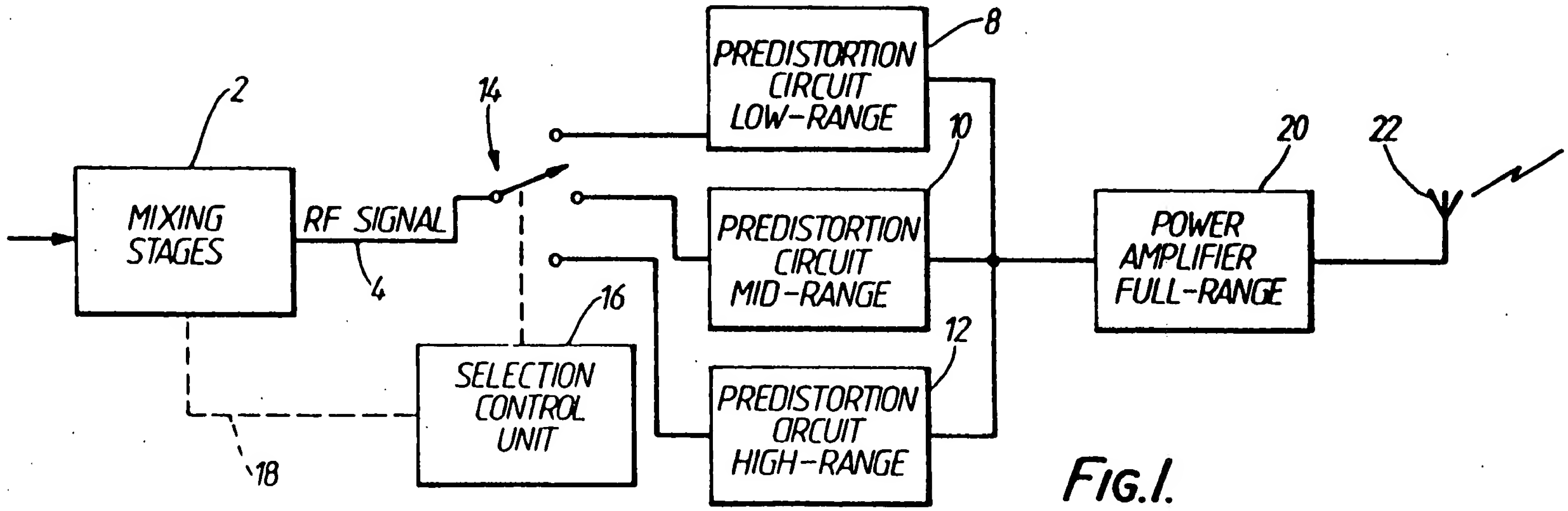


FIG.1.

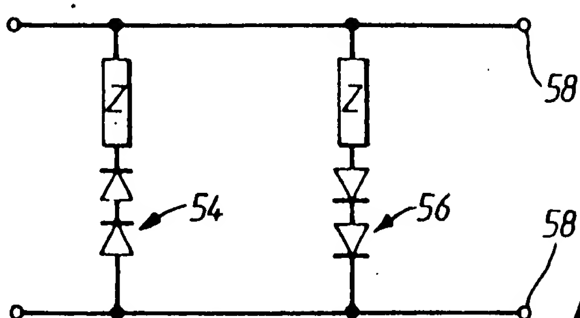


FIG.2.

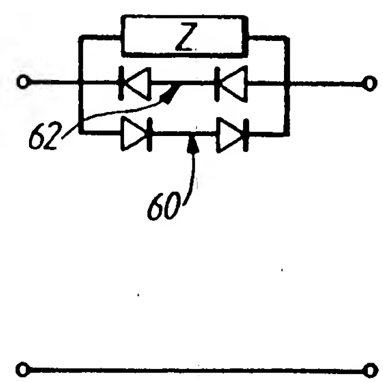


FIG.3.

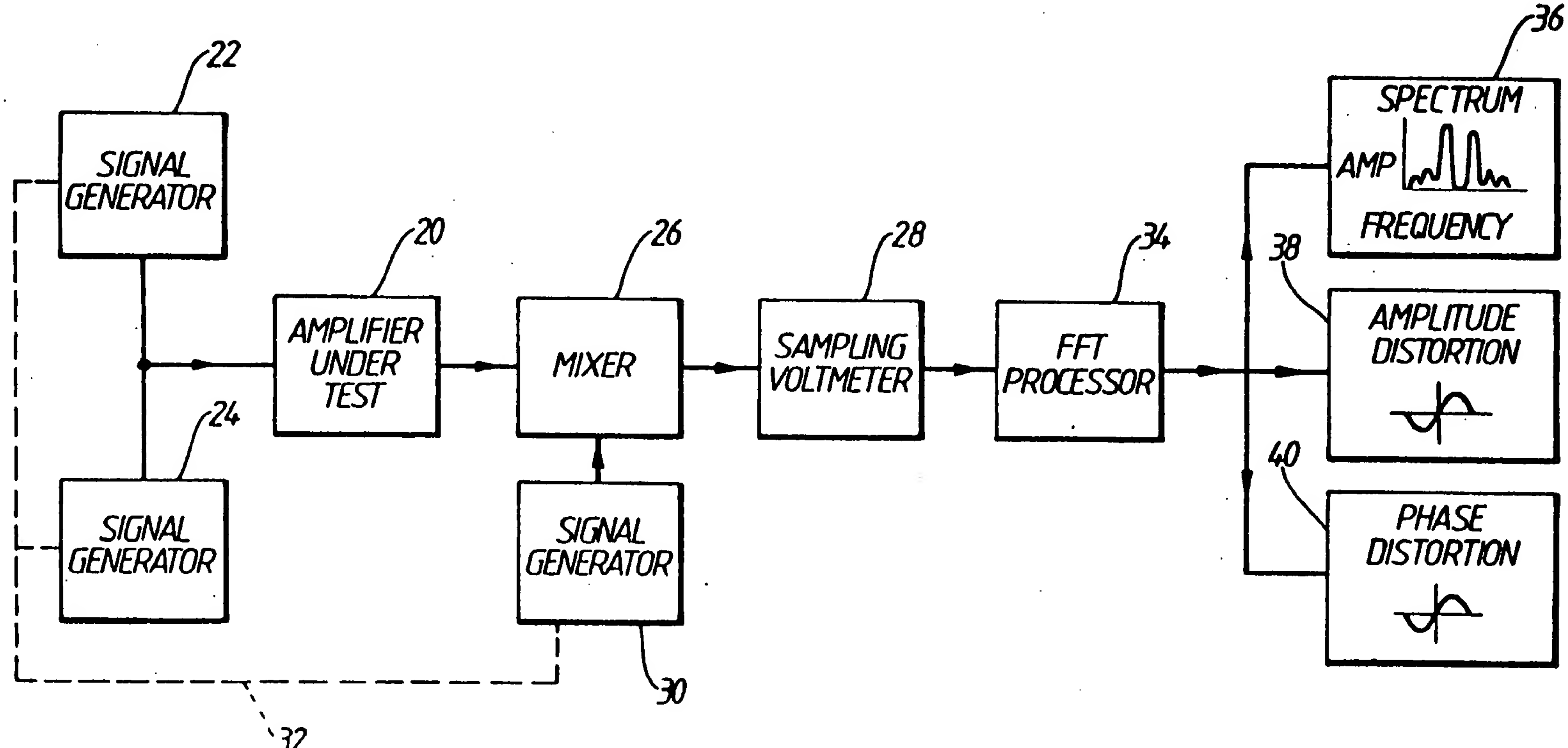

SIGNAL GENERATOR
22
SIGNAL GENERATOR
24
AMPLIFIER UNDER TEST
20
MIXER
26
SIGNAL GENERATOR
30
32
SAMPLING VOLTMETER
28
FFT PROCESSOR
34
SPECTRUM
AMP
FREQUENCY
36
AMPLITUDE DISTORTION
38
PHASE DISTORTION
40

FIG. 4.

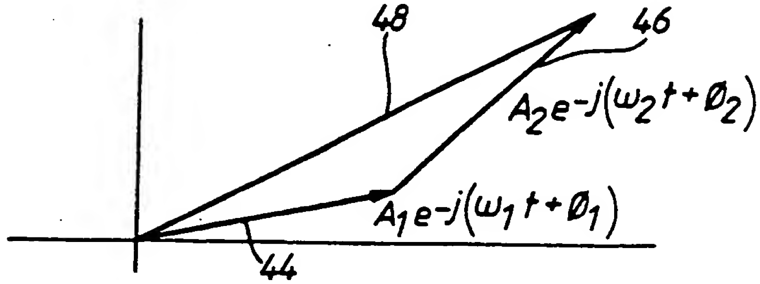


FIG.5.

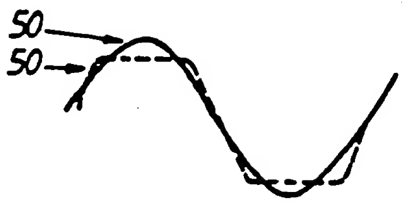
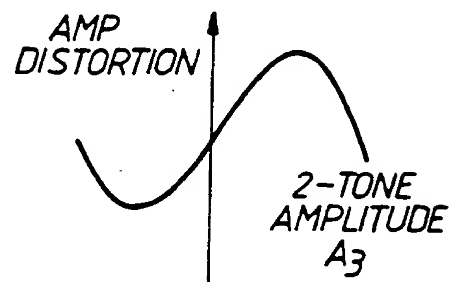


FIG.6a.



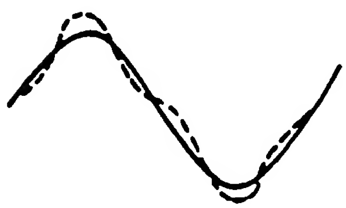
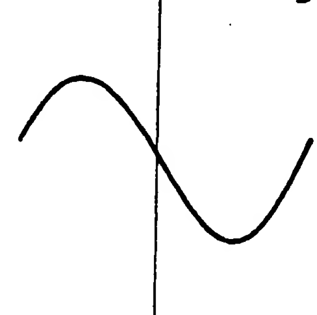


FIG.6b.



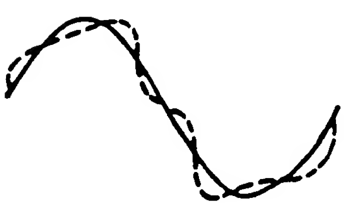
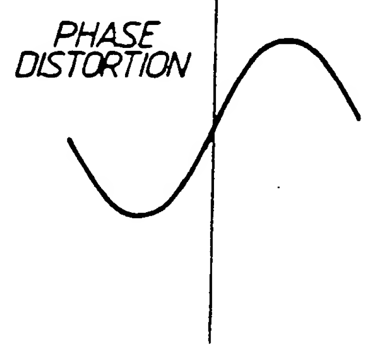


FIG.6c.



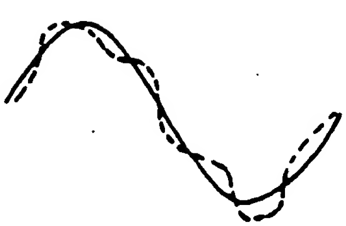
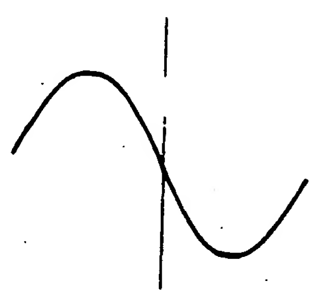


FIG.6d.



RADIO TRANSMITTERS

The present invention relates to radio transmitters and, more specifically, to the final power amplifier stage of high frequency (HF) radio transmitters.

When a transmitter is required to transmit a signal which contains components at several distinct frequencies, non-linearities in the final power amplifier give rise to intermodulation products (IMPs) at the output of the amplifier at frequencies other than those present in the input signal. The IMPs therefore distort the output and hence cause interference in adjacent channels. This effect gives rise to a significant technical problem where the frequency of the input signal to the final power amplifier stage represents information, for example if the input signal is the output of a parallel tone modem, or where the transmitter is being used to transmit several different signals at the same carrier frequency, as in an independent sideband mode of operation. For such purposes, a typical specification requires that any IMPs should be reduced by at least -35dB relative to the wanted signals. Although it is possible to achieve this with amplifiers using valves, it has hitherto been difficult and impractical to produce IMPs reduced by more than -30dB with solid state class B linear

amplifiers operating at radio frequencies.

Typically, attempts have been made to reduce distortion in such amplifiers by the use of inverted feedback techniques and a number of amplifier stages, in order to compensate for the reduction in gain produced by the negative feedback. Improvements may also be obtained by carefully selecting the biasing conditions of the transistors used. Such design considerations are well discussed in the literature. However, such techniques have been found ineffective in meeting the high specifications required.

The present invention seeks to solve the technical problem of providing a radio transmitter which is capable of suppressing intermodulation products to better than -30dB over a wide frequency range, for example the whole HF range.

The present invention accordingly provides a radio transmitter comprising a linear power amplifier for amplifying a signal at radio frequency for transmission, the amplifier comprising an input for the signal, a plurality of pre-distortion circuits each having an input and an output connected to the amplifier input, means for selectively applying the signal to the input of one of said pre-distortion circuits in dependence on its frequency, each pre-distortion circuit being adapted to produce a distortion

for a specific frequency range which is substantially equal and opposite to the distortion produced by the amplifier for that frequency range so that signals within each of the ranges are substantially undistorted at the output of the amplifier.

The use of a bank of pre-distortion circuits, together with means for selecting the required circuit at any time in dependence on the frequency range of the input signal, allows the transmitter to be used for transmitting signals over a wide frequency range without the intermodulation products causing unacceptable distortion.

The technique of pre-distortion is known in the art of electronic circuit design. For example, it has been proposed to use pre-distortion circuits interposed between a signal source and a transmission line so that the distortion imposed on the signal as it is transmitted along the line can be compensated allowing the signal to be correctly received. However, it is believed that such pre-distortion circuits have always hitherto been used in applications where the signal to be pre-distorted has a known frequency, whereas the present invention uses this technique for correcting over a wide frequency range. In order that this may be possible, it is necessary to be able to accurately measure the distortion over the whole frequency range of the

amplifier. A novel technique for carrying out this measurement, which enables this invention to be put into effect, is described herein.

In accordance with another aspect of the invention, there is provided a method of testing an amplifier in order to establish its distortion characteristics due to intermodulation products, comprising the steps of generating two signal tones to be fed simultaneously to the amplifier under test, mixing the output of the amplifier with a local oscillator frequency, sampling the voltage at the output of the mixer periodically, and carrying out a Fourier transform on the samples, in order to derive amplitude and phase information for a plurality of sample frequencies within the amplifier output, identifying distorting IMPs and determining the phase and amplitude distortion produced thereby relative to the amplitude of the vector sum of the two tones, and repeating the preceding steps for pairs of tones throughout the frequency range of the amplifier.

Using such a test, it is possible to identify the intermodulation products due to non-linear gain, and plot changes in phase and amplitude with signal amplitude which result in the distortion of the input signal throughout the frequency range. The appropriate types of pre-distortion circuits suitable for offsetting these effects can then be

selected for incorporation into the transmitter so that, whatever the radio frequency of the signal to be transmitted, the input to the amplifier can be routed through an appropriate pre-distortion circuit in order to minimise the intermodulation products. Typically, it has been found that a bank of three pre-distortion circuits can cover the whole HF range (e.g. 1.6 to 30 MHz) and ensure that all order IMPs are reduced to at least -40dB. However it is preferred to repeat the test for more than three frequencies from the range of the amplifier.

An HF radio transmitter and a method of measuring the distortion of the power amplifier in accordance with the invention will now be described, by way of example only, with reference to the accompanying diagrammatic drawings, in which:

Figure 1 is a block diagram of the HF transmitter;

Figure 2 is a pre-distortion circuit for compensating a first type of distortion;

Figure 3 is a pre-distortion circuit for compensating a second type of distortion;

Figure 4 is a test set-up for use in designing the

transmitter of Figure 1;

Figure 5 is a vector diagram for illustrating the input signal to an amplifier to be tested with the apparatus of Figure 4; and

Figures 6a to 6d show, on the left hand side amplitude versus time plots of various distorted output signals from an amplifier fed with two tones as in the apparatus of Figure 4, and, on the right hand side, corresponding plots of the amplitude or phase distortion relative to the two tone amplitude.

An HF radio transmitter as illustrated in Figure 1 comprises essentially conventional mixing stages 2 for converting an input signal, such as a voice signal or the output of a parallel tone modem, into an RF signal at an output 4. The output RF signal is passed to one of a bank of three pre-distortion circuits 8, 10, 12 via a selection switch 14, the position of which is controlled by a selection control unit 16. The outputs of all three pre-distortion circuits are connected to an input of a power amplifier 20. The output of the power amplifier is connected to an antenna 22 for transmission.

The selection control unit is shown as connected via a

selected for incorporation into the transmitter so that, whatever the radio frequency of the signal to be transmitted, the input to the amplifier can be routed through an appropriate pre-distortion circuit in order to minimise the intermodulation products. Typically, it has been found that a bank of three pre-distortion circuits can cover the whole HF range (e.g. 1.6 to 30 MHz) and ensure that all order IMPs are reduced to at least -40dB. However it is preferred to repeat the test for more than three frequencies from the range of the amplifier.

An HF radio transmitter and a method of measuring the distortion of the power amplifier in accordance with the invention will now be described, by way of example only, with reference to the accompanying diagrammatic drawings, in which:

Figure 1 is a block diagram of the HF transmitter;

Figure 2 is a pre-distortion circuit for compensating a first type of distortion;

Figure 3 is a pre-distortion circuit for compensating a second type of distortion;

Figure 4 is a test set-up for use in designing the

transmitter of Figure 1;

Figure 5 is a vector diagram for illustrating the input signal to an amplifier to be tested with the apparatus of Figure 4; and

Figures 6a to 6d show, on the left hand side amplitude versus time plots of various distorted output signals from an amplifier fed with two tones as in the apparatus of Figure 4, and, on the right hand side, corresponding plots of the amplitude or phase distortion relative to the two tone amplitude.

An HF radio transmitter as illustrated in Figure 1 comprises essentially conventional mixing stages 2 for converting an input signal, such as a voice signal or the output of a parallel tone modem, into an RF signal at an output 4. The output RF signal is passed to one of a bank of three pre-distortion circuits 8, 10, 12 via a selection switch 14, the position of which is controlled by a selection control unit 16. The outputs of all three pre-distortion circuits are connected to an input of a power amplifier 20. The output of the power amplifier is connected to an antenna 22 for transmission.

The selection control unit is shown as connected via a

control line 18 to the mixing stages 2 in order to indicate that the setting of the selection switch 14 is determined by the RF frequency of the output signal as determined by the user. The desired RF frequency of the output is, of course, used to determine the local oscillator frequencies employed during the mixing stages 2. The input means employed by the user to set the RF frequency and, therefore the local oscillator frequencies in the mixing stages may also be connected to control the selection switch. Each pre-distortion circuit is capable of producing a required mixture of amplitude and phase distortion, as determined by the previously measured distortion produced within each frequency range by the power amplifier 20, for a particular portion of the frequency range of the amplifier 20.

Because of the presence of the pre-distortion circuits, the output of the power amplifier is an amplified, but otherwise substantially identical, version of the RF signal presented at the output 4 of the mixing stages 2. In order to determine the appropriate design of the pre-distortion circuits 8, 10, and 12 and the number of such pre-distortion circuits required, it is necessary to measure the types of distortion produced by the amplifier 20 accurately throughout its operating frequency range. This may be done by employing the apparatus illustrated in Figure 4, which will now be described. Figures 2 and 3 show suitable

designs for the pre-distortion circuits 8, 10 or 12. The value and type (resistor, inductor, capacitor or combination thereof) of the impedances Z employed is determined by the distortion to be corrected as will be described in more detail later.

The amplifier 20 is typically a class B linear amplifier designed using solid state components. For testing purposes, the input signal is chosen as two RF tones at slightly different frequencies separated by, for example, 2kHz so as to generate intermodulation products, which are the particular concern of the present invention. It will be appreciated that the amplifier may also be subject to other types of distortion, such as distortion due to harmonics. The pre-distortion circuits may be able to compensate for such alternative types of distortion to some extent at the same time as dealing with the IMPs.

A two tone input to the amplifier 20 is provided by two signal generators 22, 24 operating at two distinct frequencies separated by, say, 2kHz in the HF range. The output of the amplifier is fed via a mixer 26 to a sampling voltmeter 28. The mixer 26 is provided with its second input from a signal generator 30 set to a suitable frequency to produce an output in which the two input tones generated by the signal generators 22 and 24 are mixed down to 20kHz

and 22kHz respectively. It will be appreciated that these figures are given by way of example only and other appropriate test conditions may readily be selected in dependence upon the intended application of the HF transmitter.

The frequency standards of the generators 22, 24 and 30 are connected together as shown by the dotted control line 32.

The sampling voltmeter produces digital samples of the mixed down output of the amplifier 20. The samples are fed to a computer 34 which is programmed to perform a Fourier transform on the output signal using a FFT algorithm, and also to further process the results of the FFT in order to produce plots of the spectrum of the output signal, the amplitude distortion and the phase distortion on displays or as print-outs as shown by blocks 36,38,40. It will be appreciated that these functions can readily be carried out by suitable programmes which need not be described in detail herein except for the functions which they perform which are set out more fully below.

Since the sampling voltmeter 28 may be limited in its sampling rate, it may be necessary to sample at time intervals so that each successive sample of the waveform is actually taken from a following cycle of the signal rather

than the same cycle. This produces the same results since the individual cycles, though subject to distortion, will be identical. Thus, if the FFT is to use 512 (2N) samples over a period (T) of 2 ms, samples should be taken every 0.0039 ms. However, provided all the significant frequency components are multiples of 1kHz samples may be taken at every 1.0039 ms instead. This will enable the signal output from the mixer 26 to be analysed over a frequency range of 128kHz. This is actually a larger range than may be considered strictly necessary but arises because of the requirement of the FFT algorithm to have a number of samples which is a power of 2. For the purposes of the present invention analysis of distortion due to IMPs up to the 7th order is generally all that is necessary, since higher order IMPs produce distortions which are already of a sufficiently low level and do not require further compensation. The output of the FFT contains amplitude and phase information for each of 256 (N) sample frequencies within the analysis range from 0.5kHz to 128kHz in steps of 0.5kHz (1/T). The first output from the processor 34 on display 36, which may be a CRT or plotter or both, is the spectrum of the output signal, that is the amplitude of each sample frequency versus frequency. If there is no distortion produced by the amplifier 20, this will show only the two tones at 20 and 22 kHz respectively. However, the spectrum will normally also include IMPs at various levels and harmonics. The third

order IMPs will be at 18 and 24 kHz, the fifth order at 16 and 26 kHz and so on.

In order to analyse the phase and amplitude information generated by the FFT, it is required to plot the phase and amplitude distortion versus the two tone signal amplitude. Typical such plots are shown in Figures 6a - 6d for various types of distortion. In order to produce these plots, the programme run by the computer 34 first identifies in the spectrum the two tones and computes the vector sum of these two tones as shown in Figure 5, where the first tone is identified by the vector 44 which can be expressed as $A_1 e^{-j(\omega_1 t+\phi_1)}$. The second tone is shown by the vector 46 as $A_2 e^{-j(\omega_2 t+\phi_2)}$. In the present example ω_1 = 20kHz and ω_2 = 22kHz and ϕ_1 and ϕ_2 are the relative phases of the two tones. Where the frequency standards of the signal generators 22 and 24 are connected together $\phi_1 - \phi_2$ will be a constant value. The maximum amplitudes of the signals, A_1 and A_2 are ideally equal. The vector sum of the two tones 44 and 46 is shown by the vector 48. It will be appreciated that the vector 48 rotates in time and that its amplitude will change as a function of time since the frequencies of its two components are different. The phase of the vector sum 48 of the two tones is used as a reference phase throughout the following analysis.

The average frequency of the two tones, that is 21kHz in the present example, is also used as a reference frequency. Therefore, relative to this reference, the two tones have frequencies of plus and minus 1kHz respectively, resulting in their vector sum 48 having a constant phase.

The computer programme identifies from the output of the FFT those sample frequencies at which there is a large signal, that is one having an amplitude greater than a predetermined threshold value. The threshold may be determined by reference to the amplitude of the signals at the sample frequencies corresponding to the input tones and the required level to which all IMPs are to be reduced as determined by the design specification for the amplifier. Only signals which are at IMP frequencies (e.g. ±3kHz, ±5kHz etc.) are used in the following calculations. The other large signals are monitored just as a check on the test. There should be no large signals except the IMPs and the harmonics. The phase of these IMPs relative to the reference phase is then computed. From this information it is possible to calculate the vector sum of the IMPs for a number of points, typically 200 during a 1 millisecond period, which corresponds to 1kHz and therefore covers a complete cycle of the vector sum of the two tones. The component of the vector sum of the IMPs which is in phase with the vector sum of the two tones is then computed. This

component represents the amplitude distortion and is plotted against the two tone amplitude for the purposes of the display or printout 38. The component of the vector sum of the IMPs at 90° to the reference phase represents the phase distortion. This is plotted against the two tone amplitude for output 40.

There are four basic shapes for these plots. However, any particular amplifier under test may produce modifications of these shapes. The two basic shapes of the amplitude distortion plots are shown on the right hand side in Figures 6a and 6b with the effect they have on the actual waveform shown on the left hand side where voltage is plotted against time, the solid line waveforms 50 showing the ideal, undistorted waveform, and the dotted line 52 showing the distorted waveform.

As shown in Figure 6a, there is positive amplitude distortion at low levels of the two tone amplitude and negative amplitude distortion at high levels. This is caused by the gain of the amplifier 20 decreasing with amplitude as can be seen by a comparison of the waveforms 50 and 52 on the left hand side of Figure 6a.

The amplitude distortion plot shown in Figure 6b shows the result of gain decreasing with amplitude. This type of

distortion is known as cross over distortion.

Similar plots for phase distortion are shown in Figures 6c and 6d. In Figure 6c the distortion is due to the delay through the amplifier increasing with the amplitude of the signal. The reverse situation is illustrated in Figure 6d.

Plots of the spectrum as shown on display 36, the amplitude distortion plot as shown on display 38 and the phase distortion plot as shown on display 40 are obtained and preferably printed for two tones generated by the signal generators 22 and 24 at various points in the frequency range of the amplifier 20. A plot of the waveform in time may also be generated if required to measure the frequency. These results can then be analysed to determine how best to design the predistortion circuits in order to compensate for the types of distortion found at various frequencies within the operating range of the amplifier. Typically it will be necessary to separate this operating range into a number of sub-ranges which have different distortion characteristics. For each range a suitable predistortion circuit is designed which gives the opposite change in gain and phase with amplitude to that produced by the amplifier 20.

A simple and effective way of producing distortion is to use pairs of diodes and impedances. A circuit as shown in

Figure 2 will compensate for the cross over type of amplitude distortion illustrated in Figure 6b, if the impedances Z are suitable resistances. At low amplitudes, where the diodes 54 and 56, which are preferably Schottky diodes, are non-conducting, the output voltage across terminals 58 is not affected by the predistortion circuit, whereas at higher voltages or amplitudes at which the diodes conduct, the resistance produces a greater attenuation to offset the increased grain of the amplifier. The value of the resistance is determined by the amount by which the gain increases with amplitude.

The circuit shown in Figure 3 corrects for the type of distortion illustrated in Figure 6a when the impedance Z is a resistance. In this case the circuit has no effect when the diodes 60, 62 are conducting but has the effect of decreasing the gain at low amplitudes when the diodes are off.

Corrections can be made to the phase distortion by the use of similar circuits in which Z is an inductance or a capacitance. Thus the shunt circuit of Figure 2 gives a phase change when the diodes turn on and the series circuit of Figure 3 gives a phase change when the diodes turn off. For the type of phase distortion illustrated in Figure 6c, the necessary correction can be achieved by the use of

inductors in either the circuit of Figure 2 or Figure 3. Normally since amplitude distortion will need to be corrected at the same time, this determines the choice of the type of circuit between Figures 2 and 3 and a resistive inductor will be used as the impedance Z. The use of a capacitive impedance will compensate for the type of phase distortion illustrated in Figure 6d.

Pre-distortion circuits may also be designed using the circuits shown in Figures 2 and 3 in series with the values of Z selected in accordance with the type of distortion measured using the apparatus shown in Figure 4.

The results derived from the use of the apparatus shown in Figure 4 may also be used to assist the design of the amplifier 20 by appropriate choice of bias current and selection of components.

CLAIMS

1. A method of testing an amplifier in order to establish its distortion characteristics due to intermodulation products, comprising the steps of generating two signal tones to be fed simultaneously to the amplifier under test, mixing the output of the amplifier with a local oscillator frequency, sampling the voltage at the output of the mixer periodically, and carrying out a Fourier transform on the samples in order to derive amplitude and phase information for a plurality of sample frequencies within the amplifier output, identifying distorting IMPS and determining the phase and amplitude distortion produced thereby relative to the amplitude of the vector sum of the two tones, and repeating the preceding steps for pairs of tones throughout the frequency range of the amplifier.

2. A method as claimed in claim 1, wherein the step of determining the phase and amplitude distortion comprises the steps of determining the vector sum of the

distorting IMPs and plotting its components in phase with and at 90° to the vector sum of the two tones, against the amplitude of the two tones over a time period during which the two tone amplitude completes a cycle, in order to derive plots of the amplitude and phase distortion respectively.

3. A method of testing an amplifier substantially as herein described with reference to Figures 4 to 6 of the accompanying drawings.

(0551H)

Published 1991 at The Patent Office, Concept House, Cardiff Road, Newport, Gwent NP9 1RH. Further copies may be obtained from Sales Branch, Unit 6, Nine Mile Point, Cwmfelinfach, Cross Keys, Newport, NP1 7HZ. Printed by Multiplex techniques ltd, St Mary Cray, Kent.